LINE-LINE FAULT ANALYSIS AND PROTECTION IN PV ARRAYS

PHOTOVOLTAIC PROTECTION NOTE 2

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1. INTRODUCTION

Line-line fault and its protection in solar photovoltaic (PV) arrays are discussed in this paper. Depending on fault locations, the magnitude of line-line faults in PV arrays could be high enough to damage PV modules and conductors. To better understand the fault scenarios, an example of typical line-line faults in PV arrays is introduced, followed by PV current flow explanation and current vs. voltage (I-V) characteristics analysis. To protect PV arrays from overcurrent damages, Article 690.9 of the National Electrical Code (NEC) requires overcurrent protection devices (OCPD) in PV arrays. Fuses are often utilized as OCPDs in series with PV modules. The NEC passages related to fuses in PV arrays are given in this paper. Finally, this paper will briefly explain how to choose the right size of fuses and fuse protection characteristics.

2. DEFINITION OF LINE-LINE FAULTS

A line-line fault is an accidental low-resistance connection established between two points of different potential in an electric network or system. In PV systems, a line-line fault is usually defined as a short-circuit fault among PV modules or array cables with different potential. In this paper, it is assumed that line-line faults do not involve any ground points. Otherwise, a line-line fault with any ground points can be categorized as a ground-fault.

3. CAUSES OF LINE-LINE FAULTS

Line-line faults in PV arrays may be caused by the following reasons:

- Insulation failure of cables, i.e. an animal chewing through cable insulation;
- Incidental short circuit between current carrying conductors, i.e. a nail driven through unprotected wirings;
- Line-line faults within the DC junction box, caused by mechanical damage, water ingress or corrosion.

POINTS OF INTEREST

- Line-line faults are the least common type of faults that occur in PV arrays. However, the magnitude of fault current delivered by line-line faults can be high enough to damage PV modules and conductors, increasing the risk of fire hazard and weakening the overall efficiency of the PV system
- In order to protect PV arrays from line-line faults, NEC Article 690.9 states that series overcurrent protection devices shall be required for PV modules and PV source circuits

4. TYPICAL PV SYSTEMS AND CODE REQUIREMENTS RELATED TO FUSES

A typical grid-connected PV system is schematically shown in Fig. 1. It mainly consists of a PV array, a grid-connected inverter, connection wirings and protection devices, such as overcurrent protection fuses and GFPDs. The PV array shown in Fig. 1 has n parallel PV strings, and each string has m modules in series.

Grounding

In the requirement of the NEC Article 690.41 and 690.43, there are two types of groundings in PV arrays. The first one is system grounding: the PV system with system voltage over 50 volts should be solidly system-grounded. To achieve that, the negative conductor usually is grounded via the GFPD in the PV inverter at point G (see Fig. 1). The other one is the equipment grounding: the exposed non-current-carrying metal parts of PV module frames, electrical equipment, and conductor enclosures should be grounded.

Normal Operating Condition

When the PV array is working under normal conditions, each PV string is generating current. The current flowing out of the i^{th} string is I_{i+}, where i = 1 … n. If PV strings are all electrically identical and have the same environmental working condition, then $I_{1+}=I_{2+}=\ldots=I_{n+}$. The total current flowing out of the array is $I_{pv+}= I_{1+}+I_{2+}+\ldots+I_{n+}$. Similarly, the current coming back to each string is I_{1-}, I_{2-}, … I_{n-}. Thus, the total current coming back to the array is I_{pv-} which should be equal to I_{pv+}. Since no external ground point is involved, the current flowing through the GFPD (I_g) should be zero. Notice that the PV array is supplying power, while the PV inverter absorbs the power and feeds it into the utility grid.

Kirchhoff's Current Law (KCL) requires that at any node (or junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node, where a node is any spot where two or more wires are joined. From this point of view, a ground-fault point, positive/negative bus bar, or even the inverter can be viewed as a node (or junction) in PV systems. Therefore, the current relationships of the normally operating PV array are summarized in the following equations.

- At the positive busbar: $I_{pv+} = I_{1+}+I_{2+}+\ldots+I_{n+}$
- At the negative busbar: $I_{pv-} = I_{1-}+I_{2-}+\ldots+I_{n-}$
- At the system grounding point G: $I_g = I_{pv-} - I_{pv+} = 0$
- At the inverter: $I_{pv+} = I_{pv-}$

Overcurrent Protection Devices - Fuses

In the grounded PV system, where the PV negative conductor is grounded, a single OCPD at every PV string is enough to give overcurrent protection, since the OCPD will be always in the fault path. However, in the ungrounded PV system, where both of PV positive and negative conductors are not grounded, two OCPDs should be put on the top and bottom of each PV string. Therefore, in the case of faults, at least one OCPD will be in the fault path. According to the NEC Article 690.8, the maximum current for a specific circuit in PV arrays shall be the

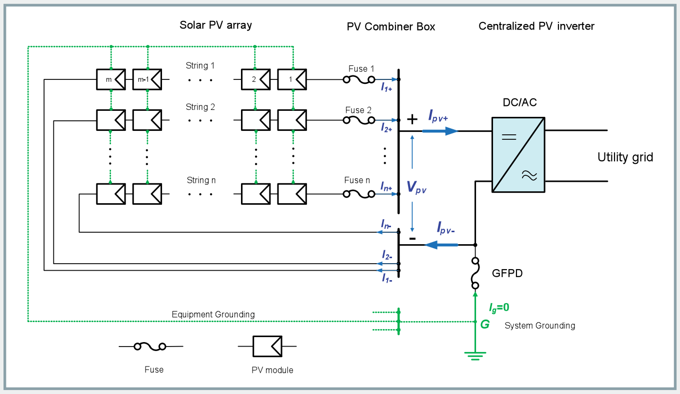

Figure 1: Schematic diagram of a typical grid-connected PV system under normal conditions

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sum of parallel module rated short-circuit current (I_{sc}) multiplied by 125 percent. In the PV system in Fig. 1, the maximum current of each PV string shall be $1.25I_{sc}$. Also, the NEC requires that overcurrent devices shall be rated no less than 125 percent of the maximum current ($1.25I_{sc}$). Consequently, by multiplying two factors together, the resulting rating of OCPDs should be no less than $1.56I_{sc}$ of PV modules.

5. LINE-LINE FAULT ANALYSIS IN PV ARRAYS

As shown in Fig. 2, a line-line fault occurs in the PV array, which may have resulted from a short circuit between the points F1 at String 1 and F2 at String 2. Therefore, the fault will cause electrical imbalance among the PV array, resulting in overcurrent into the faulted string. The fault current flowing into the faulted string is usually called backfed current (I_{back}, or reverse current), which is in the opposite direction of normal string current I_{1+}.

Generally speaking, every module, string, and whole array, whether in normal or fault condition, has its own I-V characteristics and unique maximum power point (MPP). When PV modules are connected together, their performance is determined by the interactions among them. For this reason, PV modules perform together like a chain that is only as strong as the weakest link, which is the most faulted string in the fault scenarios.

In our analysis, it is considered that the PV array is the only source of fault current. In other words, there is no overcurrent or overvoltage from any utility inverter, battery, lightning strikes or external sources. The reason is that most PV inverters are transformer-based that can provide galvanic isolation between the PV array and the utility grid. Also, the fault impedance is assumed to be zero.

Fault Current Flows

After the line-line fault, the configuration of the PV array in Fig. 2 has been accordingly changed. Specifically, the (m-2) modules below F1 at String 1 (from Module 3 to Module m) become parallel with the 2 modules below F1 at String 2 (Module m-1 and Module m). Yet modules above F1 and F2 at String 1 and String 2 respectively are in parallel. It would be easier to understand if you imagine that (m-2) modules below F1 at String 1 are sharing the same voltage as 2 modules below F2 at String 2. As a result, the voltage of m-2 modules at String 1 is pulled down to around the 2 times the open-circuit voltage of PV modules (V_{oc}).

Therefore, String 1 is significantly mismatched with other strings and the PV array's voltage might be even larger than the open-circuit voltage of faulted String 1. Instead of supplying power, String 1 may be forced to work as a load at the 4th quadrant in its I-V characteristics (see Fig. 3). The current backfeeding into String 1 from other strings is called backfed current (I_{back}, or reverse current).

I-V characteristics Analysis of Line-line Faults

The I-V characteristics in Fig. 3 can be used for current flow analysis, where V_{oc} is the open-circuit voltage of one PV module. Before the fault, the whole PV array is working at MPP (V_{mpp}, I_{mpp}). After

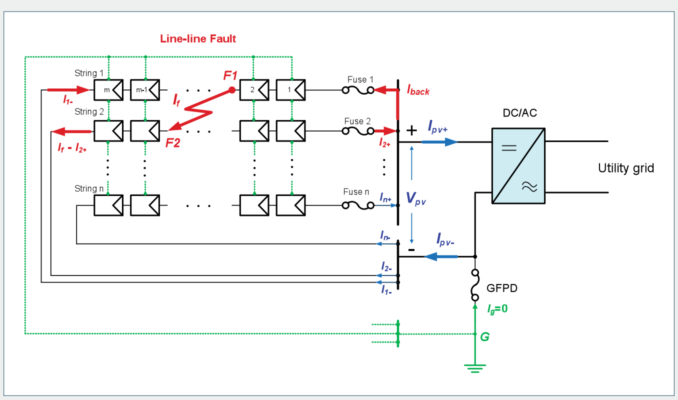

Figure 2: Schematic diagram of the PV system under a line-line fault

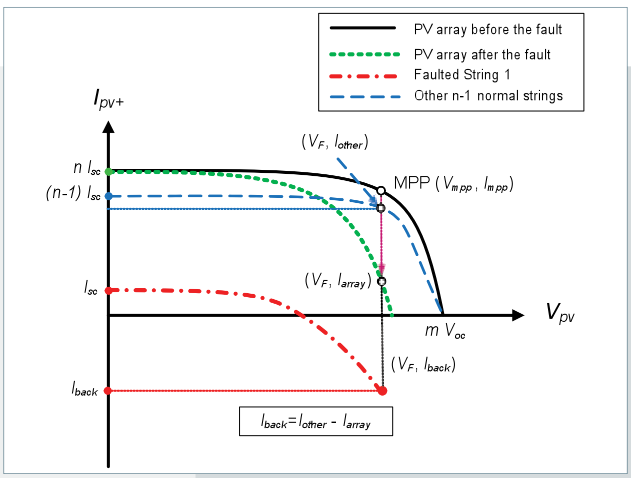

Figure 3: I-V characteristics of the PV array during a line-line fault

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the fault, the array's operating point drops vertically to (V_F, I_{array}), where V_F could be still equal to V_{mpp}. The other n-1 normal strings will work at (V_F, I_{other}). The faulted String 1 will work at (V_F, I_{back}) in its 4th quadrant of I-V characteristics as a load. According to KCL, the current relationships of the line-line fault in PV array are summarized as below.

- At the positive busbar: $I_{pv+} = -I_{back}+I_{2+}+...+I_{n+}$
- At the negative busbar: $I_{pv-} = I_{1-}+I_{2-}+...+I_{n-}$
- In the PV array: $I_{pv+} = I_{pv-}$
- At the line-line fault point F1: $I_f=I_{back} + I_{1-}$
- At the line-line fault point F2: $I_{2+}= I_f + I_{2-}$

The Worst-case Scenario of Line-line Faults

The worst case for a line-line fault is that the total current of the PV array is zero (I_{pv+}=0) and all the normal strings are backfeeding current into String 1. The backfed current into String 1 can be simply written as $I_{back}=I_{other}$. The fault scenario could be explained with the help of I-V characteristics analysis in Fig. 4. At the moment of the fault, the PV array is working at voltage V_F with I_{pv+}=0, which means the array becomes open-circuit and there is no current feeding into the PV inverter. The currents of other strings have no path to go but backfeed into String 1.

Notice that in Fig.4, I_{other} is close to but smaller than (n-1) I_{sc}. As a rule of thumb, people usually approximate I_{back} as (n-1) I_{sc} in the worst case.

Overcurrent Protection Devices - Fuses

Fuses are commonly used as overcurrent protection devices (OCPD) in PV arrays. According to the NEC Article 690.8, the fuses are rated no less than $1.56I_{sc}$. In our case, for example, there are 5 parallel strings in the PV array (n=5). The short-circuit current of PV modules is 6A (I_{sc}=6A). When carrying out the equation, (1.56 x 6 = 9) it is determined that a 9A fuse is preferred. NEC Article 240.4(B) states that the next higher standard overcurrent device rating shall be permitted to be used; therefore, if 9A fuses are not readily available the series fuses should be rated at 10A. In the worst-case of line-line fault, we can simply assume that the backfed current (I_{back}) is approximately 24A.

According to the melting time vs. current diagram in Fig. 6, the 10A fuse may take less than 0.8s to clear the maximum line-line fault (24A). Then, the fault path is detected by the fuse and the fault is interrupted.

As shown in Fig. 5, after Fuse 1 at String 1 is melted, there is no I_{back} anymore. However, the fault path between F1 and F2 still exists in the PV array. The rest of String 1 is flowing current I_{1-} into F1, where $I_f= I_{1-}$. For that reason, the fault current I_f is not completely cleared, even though I_f is greatly reduced by the fuse.

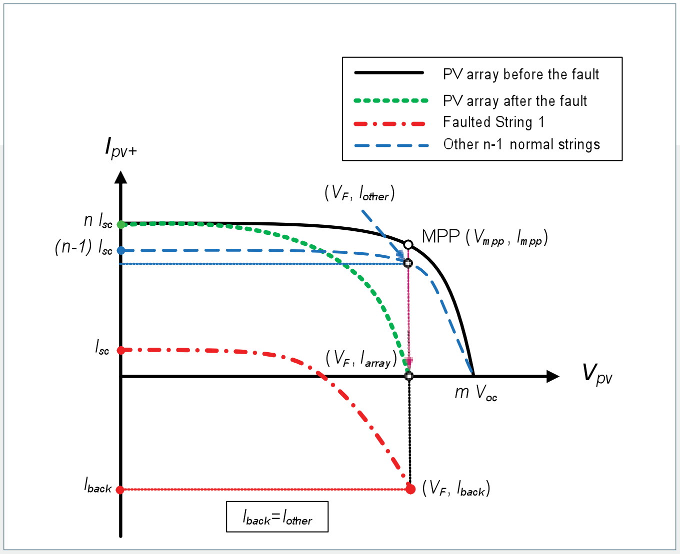

Figure 4: I-V characteristics of the PV array during the worst case of a line-line fault

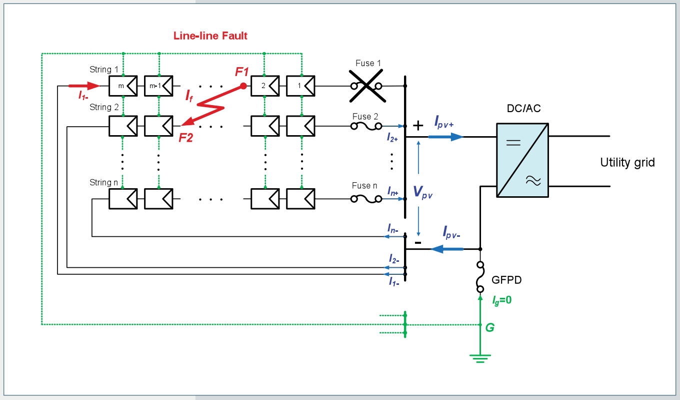

Figure 5: Schematic diagram of the PV system after the line-line fault is cleared

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In summary, the current equations after the fault clearance can be expressed as below.

- At the positive busbar: $I_{pv+} = I_{2+}+...+I_{n+}$
- At the negative busbar: $I_{pv-} = I_{1-}+I_{2-}+...+I_{n-}$
- At the line-line fault point F1: $I_f = I_{1-}$
- At the line-line fault point F2: $I_{2+} = I_f + I_{2-}$

In practice, blown fuse indication can be used in PV arrays to indicate the fault occurrence. Its light indication may tell the maintenance people at which string the fault has occurred. Therefore, the blown fuse indication can further reduce the fire hazards and other safety issues in PV arrays.

6. PRODUCT SPECIFIC

For all applications abiding by the National Electrical Code it is required that overcurrent protection be installed in photovoltaic source circuits, photovoltaic output circuits, inverter output circuits and storage battery conductors. Mersen offers a variety of fuse technologies designed to protect solar PV systems from line-line fault incidents and they are shown here for reference. More information may be obtained by visiting ep-us.mersen.com and searching for the products described below.

String fuses for line-line fault protection

Mersen recommends PV rated Midget Class fuses (10 x 38mm, 1-1/2" x 13/32") for all line-line fault protection in string circuits. PV rated Midget Class fuses offer the highest degree of protection in the smallest physical package available. They are also UL Listed for use in photovoltaic applications to UL standard 2579. For 600VDC applications select the HP6M series and for 1000VDC applications select the HP10M series.

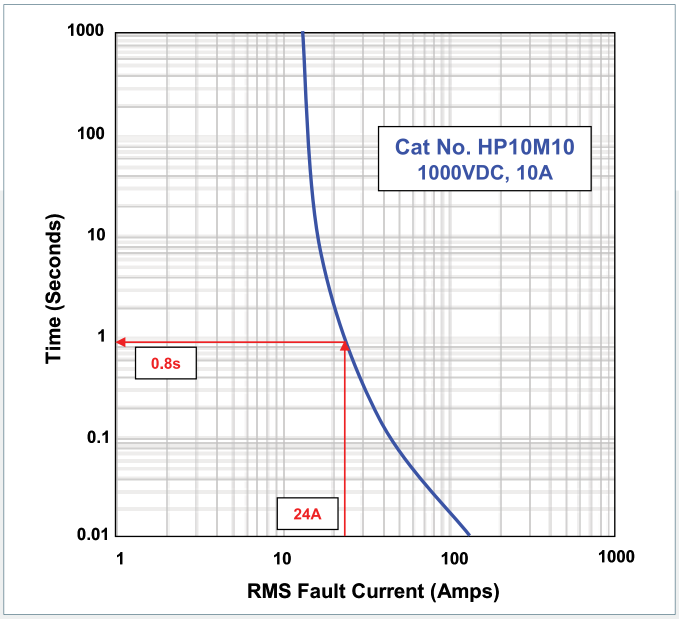

Figure 6: *Melting time vs. fault current of protection fuses*

Two types of fuse holders are available for both the HP6M and HP10M series PV rated Midget Class fuses. For internal to the string combiner box, select the touch-safe, DIN rail mountable USM series fuse holder. For outdoor use or in-line cable protection select the touch-safe FEB series fuse holder. Both fuse holder options are suitable for applications 1000VDC or less and offer tool-free fuse installation and change-outs.

Array fuses for line-line fault protection

Mersen recommends PV rated Class J fuses for all line-line fault protection in array circuits. PV rated Class J fuses offer the highest degree of protection in the smallest physical package available. They are also UL Listed for use in photovoltaic applications to UL standard 2579. For 600VDC applications select the HP6J series.

Mersen offers a variety of UL tested and certified Class J photovoltaic fuse holders. Designed for flexibility, these fuse holders allow for various wire termination capabilities including box lugs, stud terminals or a combination of the two. 90 Degrees Celsius rated wire terminals also eliminate the need for de-rating when used with 90 Degrees Celsius rated PV wire.

7. SUMMARY

Improperly detected and interrupted line-line faults can present the risk of fire hazards and/or decreased efficiencies in solar PV arrays. Excess current flow, including reverse current from adjacent strings, to faulted strings can overload conductors and/or connectors leading to overheating and risk of fire. Faulted strings can also negatively impact maximum power point tracking, ultimately affecting the efficiency and power output of the PV array.
To properly protect PV arrays from line-line fault damage, National Electrical Code Article 690.9 specifies that the overcurrent protection (fuses) be installed in photovoltaic source circuits, photovoltaic output circuits, inverter output circuits and storage battery conductors. Mersen offers a variety of solutions and technical expertise to protect against line-line fault incidents in PV arrays.

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HelioProtection by Mersen delivers engineered solutions specifically for photovoltaic applications including a full-line of UL 2579 listed fuses. Fuse solutions range from 600VDC to 1500VDC intended for photovoltaic string and array circuit protection. HelioProtection fuses comply with the UL standard 2579, CSA, European IEC standard 60269-6 and National Electrical Code requirements. For more information regarding Mersen's HP6J, HP6M, HP10J, HP10M, HP15G, and HP15M series of HelioProtection fuses visit: ep-us.mersen.com/helioprotection.

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ADDITIONAL RESOURCES

- Photovoltaic Protection Note 1: Ground Fault Analysis and Protection in PV Arrays
- Photovoltaic Protection Note 4: UL 2579 Fuses of Photovoltaic Systems
- Photovoltaic Protection Note 5: Sizing Fuses for PV per NEC

These and other Tech Topics are available on ep.mersen.com.

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